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In a microwave accelerator network, waveguide windows are employed to isolate the 10^{-7}-torr beamline vacuum from the 10^{-9}-torr vacuum of the power tube. The window is essential to long tube-life, currently in the range of $5{\times}10^4$ hours, for the 65-MW klystrons powering the Two-Mile Accelerator (TMA) [1]. Future accelerators will require shorter wavelengths to reach higher gradients, and research toward a GV/m linac presently concentrates on W-Band, at the 32nd harmonic of the 2856 MHz TMA operating frequency [2]. Engineering of such a miniature mm-wave linac requires development of a new class of mm-wave components, compatible with high-vacuum, and capable of handling high-peak power, albeit at low duty cycle. Here we report results of bench and high-power tests of such a window, the first test of such a mm-wave assembly in a working accelerator.

Conceptually the window consists of WR10 waveguide, operated in fundamental TE_{10}-mode, and a slab of dielectric filling a length of the guide. Wave transmission through a length L of lossless dielectric is described by

$$|S_{21}|^2 = \left[\cos^2\beta' L + \frac{1}{4}\left(\frac{\beta}{\beta'} + \frac{\beta'}{\beta}\right)^2 \sin^2\beta' L\right]^{-1} \qquad (1)$$

where β and β' are the guide wavenumbers in the vacuum and dielectric portions of the guide,

$$\beta = \frac{2\pi}{\lambda}\sqrt{\mu_r\varepsilon_r - \left(\frac{\lambda}{2a}\right)^2}, \qquad (2)$$

λ is the free-space wavelength, a is the waveguide width (0.10"), and μ_r and ε_r are the relative permeability and permittivity of the dielectric. For a good match, the window length should be a multiple of half the dielectric guide wavelength, or $\beta' L = n\pi$, with n an integer. In addition, Eq. (1) implies that highest bandwidth is attained with the shortest window length. We selected an $n = 2$ or "1-λ" window design as a compromise between bandwidth and ease of assembly.

As to assembly, the 0.100"×0.050" oxygen-free high-conductivity (OFE) copper WR10 rectangular waveguide is obtained unflanged from commercial extruded stock and chemically cleaned. The dielectric consists of WesCo AL-995 alumina ceramic, sliced and ground from a 3" disk, into rods of dimension .098"×.048"×2". The rods are coated with a 1-mil layer of molybdenum-manganese and fired at 1500°C forming a metallized layer for brazing. The windows are then cut to their final length of .0428" and brazed into the OFE waveguide. The waveguide flanges are attached in a separate step. They consist of 304L VAR (vacuum-arc remelt) stainless steel, machined to the standard 3/4" circular WR10 waveguide flange geometry. These are attached with a second, lower-temperature braze. After each braze step, the window is leak-checked to ensure vacuum integrity.

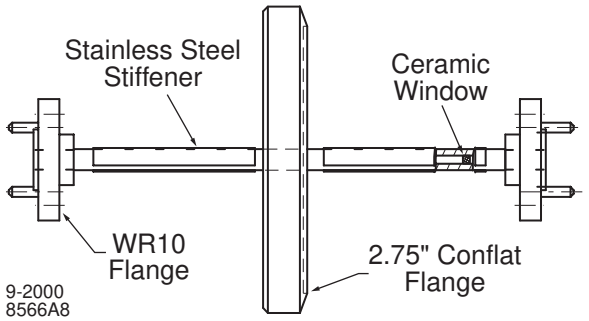

Fig. 1. Mechanical drawing of the final window assembly including rf and vacuum flanges.

One concern with this process is the difference in the thermal expansion coefficient of the ceramic ($9.3{\times}10^{-6}$) and the copper waveguide ($17{\times}10^{-6}$). Differential expansion during the 1000° braze cycle may in principle produce a gap as large as 1 mil between the dielectric and copper surfaces. For lower frequency, larger-dimension window assemblies, such differential expansion may be restrained by a molybdenum retaining wire encircling the ceramic window assembly. We omitted this step for the W-Band assembly, and encountered no problems, although one might expect that its use would produce a smaller braze fillet.

The completed window-assembly was subjected to transmission and reflection measurements in WR10 using a custom-built vector network analyser described elsewhere [3]. The results, seen in Fig. 2, were fit with the analytic result of Eq. (1), employing ε_r as a fit parameter. We infer $\varepsilon_r \approx 9.485{\pm}.03$ at 91.4 GHz. Also seen in Fig. 2 is the result of numerical simulation via the finite-difference code, *GdfidL* [4], giving good agreement.

One additional concern in this geometry is the presence of higher modes, "ghost modes", in the overmoded dielectric guide. One is particularly concerned to avoid a spurious resonance in the operating band and the added insertion loss that would result. Fig. 2 shows the power sum

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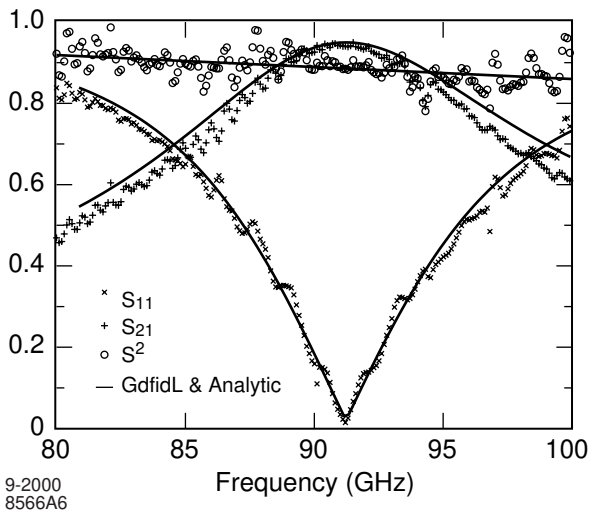

Fig. 2. Plot of measured scattering parameters, S_{11} and calculated scattering parameters for a sample window. $S^2 = S_{11}^2 + S_{21}^2$.

$|S_{11}|^2 + |S_{21}|^2$, from which we can determine the insertion loss, and inspect the operating band for ghost-modes. The observed attenuation of 0.2 dB seen in Fig. 2 is consistent with loss through the 3" copper waveguide. With such a short length of ceramic, results are not sensitive to a loss tangent in the 10^{-4} range.

After bench measurements, this window was employed on the output of a test cavity installed on a microwave accelerator at SLAC. This experiment, to be described in a later publication, produced peak power levels of 4 kW. This corresponds to a maximum electric field in the waveguide of 1.5 MV/m. The window was an essential component for this test as the solid-state components needed for power detection are not vacuum compatible, and, in any case, are most conveniently situated outside the vacuum envelope.

The design and the process appear to be mechanically sound, and robust; following the first working window, several additional windows have been fabricated, and their rf characteristics are in close agreement with the foregoing, while they have all passed leak check. Thus far we have seen no evidence of breakdown, multipactor, fracture, or puncture even while realizing that such phenomena are part of the experiment, and part of the utility of the apparatus in the first place.

To conclude, we have begun to develop vacuum-compatible components in WR10, for operation with a miniature accelerator. The immediate and initial purpose for the window was to permit monitoring of power developed in a sub-harmonic interaction circuit. Alternatives to a window include coaxial feedthrough, horn output through a window, taper to oversize guide and window. However, all of these techniques have their own challenges, and even if successful, leave one with a more complicated power calibration. More than that, they are not ideally suited for accelerator component development. With a WR10 window we can couple power to other WR10 components in a straightforward way. We expect that development of more sophisticated, *quasi-optical* accelerator components will later benefit from the calibrations and other work facilitated by this simple, yet robust window design.

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